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Application of Muon Spin Relaxation Experiment to the Mixed State Superconductors

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ABSTRACT

We discuss the use of muon spin relaxation (μ^+SR) technique to study the mixed state of superconductors. Besides the application for static vortex configurations, we argue that large vortex motion can manifest itself as a narrowed time-averaged field distribution, which in turn results in a smaller relaxation rate. A static but disordered vortex configuration can also reduce the relaxation. We summarize these arguments.

Introduction

It is well known that a muon spin relaxation (μ^+SR) technique can be successfully employed in determining the penetration lengths of superconductors. This method, however, assumes that the vortices (magnetic flux lines) are rigid rods and form a static triangular lattice. Relaxing these conditions can result in unexpected behavior—relaxation rate of μ^+SR signal becomes smaller by the introduction of either vortex motion or disorder. However, the temperature dependence of the "width" of field distribution, $\langle \Delta B^2 \rangle$, as obtained by μ^+SR differs greatly in these two cases, and gives a guide to distinguish between them.

μ^+SR Experiment

The μ^+SR technique is already widely documented.[1] Thus we give only a brief discussion here. The method of interest is the transverse muon spin geometry where magnetic field is applied perpendicular to the initial muon spin polarization. (We align the muon spins before they are implanted.) The implanted muons thermalize in a sample very quickly and start precessing in the a magnetic field. Note that at the low temperatures (say $\leq 150\,\mathrm{K}$) used for superconductivity study, the thermalized muons are localized and do not hop from site to site. Muons subsequently decay with a mean lifetime of $\tau_\mu \approx 2.2\,\mu\mathrm{s}$, emitting positrons preferentially in the direction of spin polarization. If the internal magnetic field of the sample is uniform, then the muon precession rate is the same for every muon, and the signal, which is the count of positrons along some direction versus time (corrected for the exponential decrease of surviving muons), oscillates with a constant amplitude. In a mixed state superconductor, however, the internal field varies from position to position, having maximum at the vortex core sites and decreasing as we get further way from the cores. Thus, the implanted muons precess at different frequencies depending on where they land, causing the spin ensemble to "dephase." This dephasing in turn result in the decay of μ^+SR signal amplitude with time. By inverting this relation, one obtaines the field distribution inside a superconductor, in particular the second moment $\langle\Delta B^2\rangle = \langle(B - \langle B\rangle)^2\rangle$. Typically, for a strongly type-II superconductors, the value of $\langle\Delta B^2\rangle$ is $\gtrsim 100\,\mathrm{G}^2$, and it is essential that the magnet is stable over the entire duration of cooling and data collection of the experiment.

In a similar analysis, one can obtain information on the anisotropy of the distribution (i.e. $\langle\Delta B^3\rangle$) from the phase-shift of the μ^+SR signal, but we will not go into it here.

Static Vortices

It can be shown rather simply that the static regular triangular vortex lattice gives the second moment of the field distribution,[2]

$$\langle\Delta B^2\rangle = 0.00371\frac{\phi_0^2}{\lambda^4} \tag{1}$$

where $\phi_0 = hc/2e$ is the magnetic flux quanta and λ is the penetration length of the superconductor. The relation (1) has been successfully used to determine λ in ordinary superconductors and some high-T_c materials.[3]

If the vortex configuration is disordered, the relation (1) no longer holds. As discussed recently,[4,5] increased c-axis disorder tends to reduce $\langle\Delta B^2\rangle$. This trend is intuitively understood by considering a simple model like Lawrence-Doniach model,[6] which is applicable to layered superconductors. Suppose the vortex "discs" on each layer are aligned along the z-direction (taken perpendicular to the layers) to form a triangular lattice, then clearly $\langle\Delta B^2\rangle$ is maximum. If we then move the origin of every other layer by 1/2 lattice constant or so, then $\langle\Delta B^2\rangle$ is reduced considerably.

The caveat associated with this picture is that we are assuming that there is no fluctuation in the vortex density. Inclusion of the density fluctuation has little effect on reduced $\langle\Delta B^2\rangle$ so long as it occurs within the length-scale shorter than λ. However, if the fluctuation happens in the scale larger than λ, then $\langle\Delta B^2\rangle$ can be significantly increased since some places have few vortex discs (low B) while other places have many (high B). We think that this effect is, however, not very important in real systems when the sample is field-cooled, based on the fact that such a large scale fluctuations are not energetically favorable and therefore unlikely to occur.

Whatever the type of disorder we consider, it is clear that the temperature-dependence of $\langle\Delta B^2\rangle$ for temperature independent disorder is the same as the ordered case. By a dimensional argument, the relation $\langle\Delta B^2\rangle \propto \phi_0^2/\lambda^4$ must hold such that any temperature-dependence enters only via a diverging λ as temperature approaches T_c from below.

Mobile Vortices

When vortices are mobile due to thermal fluctuations, the picture of static vortices fails and the observed $\langle\Delta B^2\rangle$ comparatively reduced due to "motional narrowing." Unlike the case of static vortices, what we must really consider is not just the spatially averaged $\langle\Delta B^2\rangle$, but rather the spatial average of the time-averaged ΔB. That is, first average ΔB at a particular site (where a muon is trapped) over the duration that the muon remains there, and then average over the space. Let us represent this time and space averaged quantity by $\langle\overline{\Delta B^2}\rangle$ where the bar indicates the time average. The fact that vortex motion reduces $\langle\overline{\Delta B^2}\rangle$ is easily understood by considering the maximum $\overline{B}_{max}$ inside a sample for two limiting cases. If the vortices are static, $\overline{B}_{max}$ is simply the value at the vortex cores, B_{core}. However, in the case of mobile vortices, the cores drift away with time, and the time average $\overline{B}_{max}$ is motionally reduced. Similar arguments apply to the minimum $\overline{B}_{min}$, except that $\overline{B}_{min}$ becomes greater with motion. In the end, we are left with smaller $[\max\overline{B} - \min\overline{B}]$, which in turn results in smaller $\langle\overline{\Delta B^2}\rangle$.

Getting the temperature dependence of $\langle\overline{\Delta B^2}\rangle$ with mobile vortices is not as easy a task. The simplest approach is to replace the different time intervals involved in evaluating $\overline{B}$ by a single time scale τ. With this approximation, we can replace the time integration over the time dependent vortex configuration by a spatial integration over the vortex probability distribution.[5] The temperature-dependence in this picture now originates in two ingredients — λ and the probability distribution, W.

For simplicity, let us consider the temperature-dependence of W for a single vortex. Since the vortex is expected to experience random walk type motion (there is no external bias), the probability distribution in question is,

$$W \sim \exp(-(\mathbf{r} - \mathbf{r}_0)^2/Dt)\,, \tag{2}$$

where $\mathbf{r}_0$ is the position of the vortex at $t = 0$ and D is proportional to the diffusion constant. Two remarks are in order: (a) As stated above, we use a single time scale τ_μ for simplicity. So we replace t by τ_μ in Eq. (2). (b) The diffusion constant D is very strongly temperature dependent. A simple thermal activation picture and the Einstein relation would give $D \sim T\exp(-V_0/kT)$ where V_0 is the relevant activation energy for the vortex.

Normally, V_0 is much greater than kT_c and hence the temperature dependence of W is too small to be important. However, for a system like high-quality single crystal $Bi_2Sr_2CaCu_2O_{8+\delta}$, we find that V_0 is sufficiently close to kT_c for the broadening of W to appear in data.[5] Our calculation using this simple approach shows that the $\langle\Delta B^2\rangle$ vs. T curve has positive curvature with sufficiently large motion, which is qualitatively quite different from the static case.

Discussion: Motion versus Disorder

The recent μ^+SR experiment on single crystal $Bi_2Sr_2CaCu_2O_{8+\delta}$ shows considerable narrowing of $\langle\overline{\Delta B}^2\rangle$ data in addition to the temperature dependence with positive curvature. There are two possible scenarios for this to happen: (a) Increased disorder with increased temperature, but vortex motion remaining small and playing little role. (b) Increased motion of vortices with temperature (and disorder as well). We feel that the first scenario is unlikely. The data show strong temperature dependence of $\langle\overline{\Delta B}^2\rangle$ even at the lowest temperature ($\sim 5\,$K). If this is merely due to the increased order of the vortex configuration with lowering temperature, we must come up with a mechanism to relax the vortex configuration at such temperature, involving macroscopic motion of vortices (scale$\sim \lambda$). However, it is well documented that such a reconfiguration of vortices does not occur within the time scale of μ^+SR experiment (several hours) at such temperatures.[7] Thus, it is much simpler to interpret this temperature dependence as due to the motion of vortices, not involving large scale movement. (The low temperature behavior is due to the "vibration" of pinned vortices.) Furthermore, scenario (B) provides a natural explanation for the observed positive curvature of $\langle\overline{\Delta B}^2\rangle$. Additional support for the scenario (B) is the reduced asymmetry of the distribution $\langle\overline{\Delta B}^3\rangle$ at higher temperatures,[5] but we will not discuss it here.

Conclusion

Though it is a difficult experiment to control and interpret, the μ^+SR technique offers the only non-perturbative probe to study both the static and dynamic behavior of vortices in superconductors. Further refinement of the technique should allow exploring higher field regimes (with high precession frequency) and better time-resolution, which can then be used to see the degree of dephasing with time. Such an improvement will control the time-averaging process of computing $\overline{B}$, and gives much more specific information about the motion of vortices in a superconductor.

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